MATTERS OF GRAVITY

The newsletter of the Topical Group on Gravitation of the American Physical Society

Number 15 **Spring 2000**

Contents

Editor

Jorge Pullin
Center for Gravitational Physics and Geometry
The Pennsylvania State University
University Park, PA 16802-6300
Fax: (814)863-9608
Phone (814)863-9597
Internet: `pullin@phys.psu.edu`
WWW: `http://www.phys.psu.edu/~pullin`

ISSN: 1527-3431

Editorial

Not much to report here. This newsletter is juicy on new research reports, which signals good times for our field. Enjoy!

The next newsletter is due September 1st. If everything goes well this newsletter should be available in the gr-qc Los Alamos archives under number gr-qc/0002027. To retrieve it send email to gr-qc@xxx.lanl.gov (or gr-qc@babbage.sissa.it in Europe) with Subject: get 0002027 (numbers 2-8 are also available in gr-qc). All issues are available in the WWW:
`http://vishnu.nirvana.phys.psu.edu/mog.html`
A hardcopy of the newsletter is distributed free of charge to the members of the APS Topical Group on Gravitation upon request (the default distribution form is via the web) to the secretary of the Topical Group. It is considered a lack of etiquette to ask me to mail you hard copies of the newsletter unless you have exhausted all your resources to get your copy otherwise.

If you have comments/questions/complaints about the newsletter email me. Have fun.

Jorge Pullin

Correspondents

- John Friedman and Kip Thorne: Relativistic Astrophysics,
- Raymond Laflamme: Quantum Cosmology and Related Topics
- Gary Horowitz: Interface with Mathematical High Energy Physics and String Theory
- Richard Isaacson: News from NSF
- Richard Matzner: Numerical Relativity
- Abhay Ashtekar and Ted Newman: Mathematical Relativity
- Bernie Schutz: News From Europe
- Lee Smolin: Quantum Gravity
- Cliff Will: Confrontation of Theory with Experiment
- Peter Bender: Space Experiments
- Riley Newman: Laboratory Experiments
- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- Stan Whitcomb: LIGO Project

TGG session in the April meeting

Clifford Will, Washington University, St. Louis
cmw@howdy.wustl.edu

This year's American Physical Society "April" Meeting will be held in Long Beach, CA, April 29 - May 2. Your TGG program committee has organized the following invited and contributed sessions. The annual TGG business meeting will be held on April 30. In addition to our TGG sessions, there will be other interesting sessions, including one on first results from the Chandra satellite, one on measurements of G, and 9 general interest plenary talks. For further information about the meeting, consult the APS website http://www.aps.org/meet/APR00/

TGG INVITED SESSIONS

GRAVITATION IN THE 21ST CENTURY
(a report on the recent NRC Decadal Survey of Gravitational Physics)
11:00 a.m., Saturday, April 29

James Hartle The Future of Gravitational Physics

Peter R. Saulson Prospects for Gravitational Wave Detection

Saul Teukolsky Black Hole Physics: Prospects for the Coming Century

Eric G. Adelberger High-Precision tests of the Gravitational Standard Model

Abhay Ashtekar Challenges and Opportunities in Quantum Gravity

GAMMA RAY BURSTS: THE CENTRAL ENGINE
(with Division of Astrophysics)
2:30 p.m., Saturday, April 29

Chryssa Kouveliotou Recent developments in gamma-ray burst research

Stan Woosley Collapsars, Gamma-Ray Bursts, and Supernovae

Maximilian Ruffert Merging Neutron Star - Black Hole Binaries

Wai-Mo Suen Numerical Relativity and Neutron Star Mergers

Sam Finn Detecting gravitational-waves from gamma-ray burst sources

GRAVITY AT SHORT RANGE
(joint with Division of Particles and Fields)
8:00 a.m., Tuesday, May 2

Nima Arkani-Hamed Accessible Extra Dimensions

John C. Price Experiments on Gravitational Strength Forces below 1 cm

Aharon Kapitulnik Measurements of Gravity at sub-millimeter scales using cantilever technology

Greg Landsberg Probing Extra Dimensions in Collider Experiments

Lisa Randall Theoretical Scenarios

GRAVITATIONAL RADIATION - EXPERIMENT 11:00 a.m., Sunday, April 30

TGG BUSINESS MEETING 5:30 p.m., Sunday, April 30

GRAVITATION: QUANTUM, SINGULAR AND ALTERNATIVE 11 a.m., Monday, May 1

GRAVITATIONAL RADIATION - THEORY AND NUMERICAL RELATIVITY 2:00 p.m., Monday, May 1

NRC report

Beverly Berger, Oakland University
berger@oakland.edu

The Committee on Gravitational Physics of the National Research Council has completed its review of the past 10 years of gravitational physics research and made its recommendations for the next 10 years. The committee's report, "Gravitational Physics: Exploring the Structure of Space and Time" is available from the National Academy Press website at

http://www.nap.edu/catalog/9680.html

Be sure to click on "READ" for the on-line version.

MG9 Travel Grant for US researchers

Jim Isenberg, University of Oregon
jim@newton.uoregon.edu

At the University of Oregon have applied for an NSF grant to fund travel to MG IX in Rome, Italy, this July 2-8. While the grant has not been approved, there is a reasonable chance that it will be. People who wish to apply for these funds should fill out the application form below, and send it (before 15 March)

Note the following: 1) A US scientist is one who generally works in the US. Nationality is not relevant. 2) The funds can only be used to cover transportation to and from Rome. Housing and registration costs must be met otherwise. 3) US carriers, if available, must be used. (You are advised to consider making airline reservations as soon as possible to secure a good fare) 4) The selection of the people to receive travel support will be made by a panel of experienced US scientists (both theorists and experimentalists), based on the information on the returned application forms. Preference will be given to those with NSF grants and those with no federal research support.

Please disseminate this information to your colleagues.

Application for International Travel Grant Funds for U.S. Participants in MG IX.

Name

Address*

e-mail address*

Phone/Fax number*

Present position and home institution

Previous positions and home institutions for the past three years

Date and place of most advanced degree

Area of research

Are you: Plenary speaker - Workshop chair - Lead Author on Contributed paper

List all current grants in gravitational physics

List the international meetings in gravitational physics attended during the past three years (note if you have received NSF travel funds since GR14):

Estimate Travel Cost for MG IX

Please add anything else you wish the selection committee to know. If you think that your work may be unfamiliar to us, please ask a senior scientist to send us a short letter of recommendation.

Signature Date

Return this application by 15 March to Gayle Asburry: Dept of Math, Univ of Oregon, Eugene, OR 97403 or e-mail to asburry@math.uoregon.edu

*State address, phone number, etc, for March through June

How many coalescing binaries are there waiting to be detected?

Vassiliki Kalogera, Harvard-Smithsonian Center for Astrophysics
vkalogera@cfa.harvard.edu

The inspiral and coalescence of close binaries with two compact objects, neutron stars (NS) or black holes (BH), are considered to be some of the most important sources of gravitational waves. Assessment of their detectability is crucial and depends on two factors: (i) The strength of the inspiral gravitational radiation signal in the frequency range of interest, which determines the maximum distance ($D_{\rm max}$) out to which coalescing binaries could be detected given a certain detection system. For LIGO II (and I), the most recent estimates of $D_{\rm max}$ are reported in the latest version of the LSC White Paper on Detector Research and Development [1]: 450 Mpc (20 Mpc) for NS–NS binaries, 1000 Mpc (40 Mpc) for NS–BH binaries, and 2000 Mpc (100 Mpc) for BH–BH binaries (assuming $10\,{\rm M}_\odot$ BH). (ii) The rate of coalescence events out to these maximum distances. This rate depends on our expectation of the Galactic coalescence rates and their extragalactic extrapolation. Using the above $D_{\rm max}$ estimates and the method of extrapolation to galaxies other than the Milky Way developed by Phinney (1991) [2] (based on the blue-light luminosities associated with galaxy star formation history), it can be estimated that the Galactic coalescence rates required for a LIGO II detection rate of 2–3 events per year are $\sim 10^{-6}\,{\rm yr}^{-1}$ (NS–NS coalescence) and $\sim 10^{-8}\,{\rm yr}^{-1}$ (BH–BH coalescence).

On the issue of detectability then the main question concerns estimates of the Galactic coalescence rates derived based on our current astrophysical understanding of coalescing binaries. This question has occupied the astrophysics community for about ten years now. A number of studies have appeared in the literature with a wide range of results that often create a confusing picture for the outside reader. In this article I will try to present an up-to-date review focusing on our best current bet for a coalescence rate estimate and its most important uncertainties.

Purely theoretical coalescence rates can be predicted using population synthesis models of the formation of coalescing binaries, given an evolutionary formation path. The basic idea is that an ensemble of primordial binaries, formed at a rate in accordance with the Galactic star formation rate, is followed as it evolves through a long sequence of evolutionary stages, including multiple phases of mass and angular-momentum losses, stable or unstable mass transfer, supernovae or stellar collapse events. The details of these physical processes are not very well understood at present, so a number of assumptions are necessary to obtain coalescence rate estimates and exhaustive parameter studies are essential in assessing the robustness of the results. Recent studies [3],[4],[5],[6] have mainly focused on the effect of kicks imparted to compact objects at birth, as well other uncertain factors at various levels of detail. The results obtained by varying the kick magnitudes solely lie in the ranges $< 10^{-7} - 5\times10^{-4}\,{\rm yr}^{-1}$, $< 10^{-7} - 10^{-4}\,{\rm yr}^{-1}$, and $< 10^{-7} - 10^{-5}\,{\rm yr}^{-1}$, for NS–NS, NS–BH, and BH–BH coalescence events, respectively. Other uncertain factors can *further* change the estimates by factors of 10–100. Given such wide ranges of predicted rates, it becomes evident that population synthesis calculations have a rather limited predictive power and provide fairly loose constraints on coalescence rates.

The observed sample of NS–NS binaries with coalescence times shorter than 10^{10} yr consists

of only two systems, PSR B1913+16 and PSR B1534+12, but provides us with an alternative way of estimating the NS–NS coalescence rate. Phinney (1991) [2] and Narayan et al. (1991) [7] obtained the first empirical estimates based on models for radio-pulsar selection effects and estimates of the lifetimes of the observed systems. Both studies obtained an estimate of $10^{-6}\,\mathrm{yr}^{-1}$ assuming a NS–NS Galactic scale height of 1 kpc. Since then, the increase of the Galactic volume covered by radio pulsar surveys and an upward revision of the distance estimate to PSR B1534+12 have lead to a reduction of the NS–NS coalescence rate. On the other hand, upward corrections have been applied, which account for beaming effects and the faint end of the pulsar luminosity function. Recent estimates [8],[9],[10],[11] lie in the range $6 \times 10^{-7}\,\mathrm{yr}^{-1}$ to $8 \times 10^{-6}\,\mathrm{yr}^{-1}$. I am currently involved in a study [12] in which the issues of NS–NS scale height, pulsar lifetimes, beaming, and small-number sample and faint-pulsar corrections are examined in detail. Our best estimate for the Galactic coalescence rate is $1 - 2 \times 10^{-5}\,\mathrm{yr}^{-1}$. Uncertainties dominated by the faint-pulsar luminosity correction (which is typically large and uncertain because of the small-number sample of close NS–NS) could decrease this estimate to $\sim 10^{-6}\,\mathrm{yr}^{-1}$ or raise it up to $\sim 10^{-4}\,\mathrm{yr}^{-1}$. Although a significant uncertainty in the estimate persists, it is clear that the empirical estimates of the NS–NS coalescence rate are more robust than those calculated purely theoretically.

Recently, a new candidate NS–NS system (PSR J1141-6545) was discovered by the ongoing Parkes Multibeam pulsar survey [13]. Although the nature of the pulsar companion needs confirmation (it could be a white dwarf) and the associated selection effects have not been modeled yet, a lower limit to its contribution to the empirical NS–NS coalescence rate can be estimated based solely on the pulsar lifetime [12]. Unlike the other two systems, PSR J1141-6545 is young with a characteristic age of only 1.45 Myr and its total lifetime is estimated to 30.5 Myr. Even if it is the only such pulsar in the Galaxy, this newly discovered system can contribute to the coalescence rate by at least $\simeq 3 \times 10^{-8}\,\mathrm{yr}^{-1}$. Taking into account all the corrections, a 10-fold upward revision of the rate would require that 50 to 200 such pulsars exist in our Galaxy.

Information about the detectability of coalescing NS–NS systems can also be obtained if robust limits to the rate can be derived. So far a safe upper limit of $\sim 10^{-4}\,\mathrm{yr}^{-1}$ has been derived based on two different arguments: (i) the absence (until recently) of any young pulsars in close NS–NS binaries [14],[10] (this upper limit will be increased by a multiplication factor equal to the estimated number of pulsars similar to PSR J1141-6545 in the Galaxy), and (ii) the maximum ratio of the formation frequencies of coalescing NS–NS and isolated pulsars similar to those found in NS–NS systems (freed at the second supernova) and an empirical estimate of the birth rate of such isolated pulsars [15].

If we compare the estimated coalescence rates to the requirement for a LIGO II detection rate of 2–3 events per year, then we can expect a detection rate in the range of 1–10 (based on the more robust empirical estimates) or even up to ~ 100 per year, based on the derived upper limits. For NS–BH and BH–BH coalescence, we can only rely on purely theoretical estimates. Despite the large uncertainties (typically 3–4 orders of magnitude), the ranges for their most part lie *above* the requirements for a couple of events detected per year by LIGO II and imply detection rates of a few up to even 100-1000 per year. For LIGO I, a simple volume scaling shows that detection of NS–NS inspiral is rather unlikely, while BH binaries could be detected provided that the upper ends of the ranges are closer to reality.

So far we have dealt with coalescing binaries formed in galactic fields. Formation of coalescing binaries in globular clusters involves a whole range of very different processes mostly domi-

nated by stellar interactions and also differs because of the absence of ongoing star formation over timescales comparable to the lifetimes of these binaries. The contribution of clusters to NS–NS coalescence has been found to be negligible [2]. However, a recent study [16] examined the formation of BH–BH binaries with coalescence times shorter than 10^{10} yr and concluded that their formation rates are quite high possibly leading to LIGO II detection rates of ~ 100 per year (one event per two years for LIGO I). Although these predicted rates may be lower because of necessary cosmological corrections and loss of systems with very short coalescence timescales, they are still more than encouraging!

Overall, it seems fair to say that, despite the uncertainties in the rate estimates, the prospects for gravitational wave detection from the inspiral of compact binaries appear to be quite promising, especially for the upgraded LIGO interferometers.

References:

[1] Gustafson, E., Shoemaker, D., Strain, K., and Weiss, R. 1999, *LSC White Paper on Detector Research and Development* (LIGO-Project document, September 11).

[2] Phinney, E.S. 1991, *ApJ*, 380, 17.

[3] Lipunov, V.M., Postnov, Prokorov, 1997, *MNRAS*, 288, 245.

[4] Fryer, C.L., Burrows, A., & Benz, W. 1998, *ApJ*, 496, 333.

[5] Portegies-Zwart, S.Z., and Yungel'son, L.R. 1998, *A&A*, 332, 173.

[6] Brown, G.E., and Bethe, H. 1998, *ApJ*, 506, 780.

[7] Narayan, R., Piran, T., & Shemi, S. 1991, *ApJ*, 379, 17.

[8] van den Heuvel, E.P.J., and Lorimer, D.R. 1996, *MNRAS*, 283, 37.

[9] Stairs, I.H., et al. 1998, *ApJ*, 505, 352.

[10] Arzoumanian, Z., Cordes, J.H., Wasserman, I. 1998, *ApJ*, 520, 696.

[11] Evans, T., et al. 2000, to appear in the proceedings of the XXXIVth Rencontres de Moriond on "Gravitational Waves and Experimental Gravity", Les Arcs, France.

[12] Kalogera, V., Narayan, R., Spergel, D., & Taylor, J. 2000, to be submitted to ApJ.

[13] Manchester, R.N., et al. 2000, to appear in *Pulsar Astronomy - 2000 and Beyond*, eds. N. Wex, M. Kramer, & R. Wielebinski.

[14] Bailes M. 1996, in *Compact Stars in Binaries*, IAU Symp. No. 165, eds. J. van Paradijs, E.P.J. van den Heuvel, and E. Kuulkers (Dordrecht: Kluwer Academic Publishers), 213

[15] Kalogera, V., and Lorimer, D.R. 2000, *ApJ*, 530, in press, `astro-ph/9907426`.

[16] Portegies-Zwart, S.F., and McMillan, S.L.W. *ApJ Letters*, 528, L17 (2000).

Black hole critical phenomena: a brief update

Patrick R Brady, University of Wisconsin-Milwaukee
patrick@gravity.phys.uwm.edu

The analogy between critical phenomena in statistical physics and interesting dynamical features observed in numerical simulations of spherical self-gravitating scalar field collapse was introduced by Choptuik [1]. Choptuik numerically evolved one parameter p families of initial data. For all families, he found a critical value of the parameter, p^* say. No black hole formed in evolutions with $p < p^*$ and black holes always formed in evolutions with $p > p^*$. Choptuik also observed two fundamental properties of solutions with $p \simeq p^*$. First, they exhibited self-similar echoing, later called discrete self-similarity, which was universal. Second, the mass of black holes formed in marginally super-critical collapse obeyed a scaling law $M_{\rm BH} \propto |p - p^*|^\gamma$ with $\gamma \simeq 0.37$ independent of the initial data family. Choptuik speculated that there was a universal solution which acted as an intermediate attractor when $p = p^*$. Since this ground-breaking work, a considerable literature has emerged on critical phenomena in gravitational collapse.

Different matter models, couplings and symmetries were examined in an effort to understand the extent of the universality and scaling noted by Choptuik. In a tremendous tour-de-force, Abrahams and Evans [2] explored the collapse of axisymmetric gravitational wave configurations; they found tentative evidence for discrete self-similarity and a scaling law for black hole mass with $\gamma \simeq 0.37$. Evans and Coleman [3] considered the collapse of radiation fluid spheres; they found that near critical evolutions exhibit continuous self-similarity (CSS), and that the scaling exponent for the black hole mass is $\gamma \simeq 0.36$. Evans and Coleman went further by constructing the CSS solution which is the intermediate attractor in perfect fluid collapse. Koike *et al.* [4] examined the spectrum of perturbations around this solution and demonstrated that the solution is one mode unstable. The critical exponent γ is related to the growth rate β of the unstable mode as $\gamma = 1/\beta$. The completion of this program, as suggested by Evans and Coleman, established the origin of the mass scaling law for black hole mass. Maison [5] used the method to argue that the scaling exponent would be a function of k for equations of state with $P = k\rho$ where P is pressure and ρ energy density.

Since the last report in *Matters of Gravity*, this field has consolidated further. It is now well understood what constitutes a critical solution for gravitational collapse, and several important "analytic" results indicate our understanding of critical phenomena is correct. Following the work of Koike *et al.*, Gundlach applied perturbative techniques to the massless scalar field critical solution which he computed directly [6,7]. His computation of the critical exponent agreed with the experimentally observed value. This, and the work of Koike *et al.*, are excellent examples of retrodiction; having the answer, a direct computation was performed to establish the critical exponent. But the techniques used to identify critical solutions and to compute the associated scaling exponents have been applied by Gundlach, Martin-Garcia, Maison and others to discover new critical solutions and predict associated critical exponents. This work was vindicated by subsequent numerical computation. For example, analytic calculations predicted a periodic wiggle superimposed on the mass scaling law for massless scalar field collapse [7,8]; the oscillations were found numerically by Hod and Piran [8]. Charged scalar field collapse was predicted to behave as uncharged massless scalar field near the critical point; the charge obeying a scaling law similar to the mass but with a critical exponent $\delta = 0.88$. This was also confirmed by Hod and Piran [9].

Researchers have continued to explore the parameter space of solutions for a variety of matter models bringing a wealth of new phenomenology to light. Choptuik, Chmaj and Bizon [10] studied the collapse of SU(2) Yang-Mills fields. They found two distinct types of critical behavior. In Type II transitions, the critical solution is discretely self-similar and black holes of arbitrarily small mass can form. The appearance of Type I transitions was a new feature in black hole critical phenomena; the critical solution is the static Bartnik-McKinnon solution and black hole formation turns on at finite mass. Type I phase transitions have also been found for massive scalar fields [11] and $SU(2)$ Skyrme models [12]. Further phenomenology has also been identified in studies of the magnetic Yang Mills fields. Choptuik, Hirschmann and Marsa [13] found transitions between black holes formed in Type I collapse and black holes formed in Type II collapse; the critical solution is an unstable colored black hole.

Interestingly, numerical confirmation of Maison's predictions were not forthcoming until late in 1997 [14]. With this came new understanding of regular self-similar perfect fluid solutions. Folklore had it that no regular self-similar solutions existed for $k > 0.899$ in the equations of state $P = k\rho$. Neilsen and Choptuik found evidence for such solutions in their collapse simulations, and re-investigated the exact self-similar solutions. They found that the nature of the sonic horizon changes when $k > 0.899$ *but* regular self-similar solutions do exist. The surprise of this was emphasized when Neilsen and Choptuik evolved stiff fluids with $k = 1$ and found a CSS critical solution. Since an irrotational perfect fluid with $k = 1$ can be recast as a scalar field with timelike gradient, Neilsen and Choptuik had found a scalar field solution with a CSS critical solution in contrast top Choptuik's original work. This issue is under active investigation.

Lack of space prohibits detailed discussion of the many other lines of research that have been pursued. Astrophysical implications of formation of tiny black holes in the early universe have been considered. Attempts have been made to understand the semi-classical corrections to Type II critical phenomena. The symmetries of the critical solutions led to the development symmetry seeking coordinates [15] which might be useful in other circumstances. In a mammoth effort, Gundlach, Martin-Garcia and Garfinkle [16] have examined small deviations from spherical symmetry and predicted scaling relations for angular momentum in Type II transitions. The interested reader is referred to Gundlach's review article [17] for more details.

So what does the future hold. There is little doubt that axisymmetric (and ultimately 3-dimensional) collapse simulations will bring a wealth of new phenomenology. Significant effort is under way to produce accurate and robust codes to perform the parameter space surveys that are needed. Just as the initial study of massless scalar field collapse required the introduction of new techniques into numerical relativity, ongoing research should foster further developments.

References:

[1] M. W. Choptuik, *Phys. Rev. Letters* **70**, 9–12 (1993).

[2] A. M. Abrahams and C. R. Evans, *Phys. Rev. Letters* **70**, 2980 (1993).

[3] C. R. Evans and J. S. Coleman, *Phys. Rev. Letters* **72**, 1782 (1994).

[4] T. Koike, T. Hara, and S. Adachi, *Phys. Rev. Lett.* **74**, 5170 (1995), gr-qc/9503007.

[5] D. Maison, *Phys. Lett. B* **366**, 82 (1996).

[6] C. Gundlach, *Phys. Rev. Lett.* **75**, 3214 (1995), gr-qc/9507054.

[7] C. Gundlach, *Phys. Rev. D* **55**, 695 (1997), gr-qc/9604019.

[8] S. Hod and T. Piran, *Phys. Rev. D* **55**, 440 (1997), gr-qc/9606087.

[9] S. Hod and T. Piran, *Phys. Rev. D* **55**, 3485 (1997),
r-qc/9606093 http://xxx.lanl.gov/abs/gr-qc/9606093.

[10] M. W. Choptuik, T. Chmaj, P. Bizon, *Phys. Rev. Lett.* **77**, 424 (1996), gr-qc/9603051; P. Bizon and T. Chmaj, *Acta Phys. Polon.* **B29**, 1071 (1998), gr-qc/9802002.

[11] P. R. Brady, C. M. Chambers, and S. M. C. V. Goncalves, *Phys. Rev. D* **56**, 6057 (1997), gr-qc/9709014.

[12] P. Bizon, T. Chmaj, *Phys. Rev.* **D58**, 041501 (1998), r-qc/9801012
http://xxx.lanl.gov/abs/gr-qc/9801012.

[13] M. W. Choptuik, E. W. Hirschmann, and R. L. Marsa, *Phys. Rev.* **D60**, 124011 (1999), gr-qc/9903081.

[14] D. W. Neilsen and M. W. Choptuik, *Class. Quant. Grav.* **17**, 761 (2000), gr-qc/9812053; P. Brady and M. J. Cai, in *Proceedings of the 8th Marcel Grossman Meeting*, T. Piran, ed. World Scientific, Singapore, 1999.

[15] D. Garfinkle and C. Gundlach, *Class. Quant. Grav.* **16** 4111 (1999), gr-qc/9908016.

[16] C. Gundlach, "Critical gravitational collapse of a perfect fluid with p=k*rho: Non-spherical perturbations", gr-qc/9906124; C. Gundlach and J. M. Martin-Garcia, "Gauge-invariant and coordinate-independent perturbations of stellar collapse. I: The interior," gr-qc/9906068; D. Garfinkle, C. Gundlach, and J. M. Martin-Garcia, *Phys. Rev.* **D59**, 104012 (1999), gr-qc/9811004.

[17] C. Gundlach, "Critical phenomena in gravitational collapse," to appear in Living Reviews in Relativity, gr-qc/0001046.

Optical black holes?

Matt Visser, Washington University, St. Louis visser@tui.wustl.edu

The last few years have seen a lot of interest in condensed matter analogues for classical Einstein gravity. The most well-developed of these analog models are Unruh's acoustic black holes (dumb black holes), but attention has recently shifted to the optical realm. The basic idea is that in a dielectric fluid the refractive index, the fluid velocity, and the background Minkowski metric can be combined algebraically to provide an "effective metric" that can be used to describe the propagation of electromagnetic waves. The most detailed and up-to-date implementation of this idea is presented in very recent papers by Leonhardt and Piwnicki [1–4], which are based on a thorough re-assessment of the very early work of Gordon [5].

To get the flavour of the way the effective metric is set up, start with a dispersionless homogeneous stationary dielectric with refractive index n and write the electromagnetic equations of motion as

$$\left(-n^2 \frac{d^2}{dt^2} + \nabla^2\right) F^{ab} = 0.$$

If you write this in terms of the Minkowski metric η^{ab} and dielectric 4-velocity V^a, then

$$\left\{-n^2 (V^c\, \nabla_c)^2 + [\eta^{cd} + V^c\, V^d]\, \nabla_c \nabla_d\right\} F_{ab} = 0.$$

Now promote the refractive index and 4-velocity to be slowly-varying functions of space and time. (Slowly varying with respect to the wavelength and frequency of the EM wave.) The preceding formula *suggests* that it is possible to write

$$\frac{1}{\sqrt{-g}}\, \partial_c \left(\sqrt{-g}\; g^{cd}\; \partial_d F_{ab}\right) = 0,$$

with the (inverse) metric being proportional to

$$g^{ab} \propto \eta^{ab} - (n^2 - 1)\; V^a\; V^b.$$

A more detailed calculation confirms this suggestion, and also lets you fix the overall conformal factor (it's unity, at least in Gordon's implementation). If you are only interested in ray optics then fixing the conformal factor is not important. Once you have this effective metric in hand, applying it is straightforward (even if the physical situation is unusual).

There are a few tricks and traps:

1. The 4-velocity is normalized using the Minkowski metric $\eta_{ab}\; V^a\; V^b = -1$, and in this particular subfield it seems to have become conventional to define $V_a = \eta_{ab} V^b$, so that the index on the 4-velocity is lowered with the Minkowski metric. (But for everything else you raise and lower indices using the effective metric.) The metric itself is then

$$g_{ab} = \eta_{ab} - (n^{-2} - 1)\; V_a\; V_b = [\eta_{ab} + V_a\; V_b] - n^{-2}\; V_a\; V_b.$$

2. The analogy with Einstein gravity only extends to the kinematic aspects of general relativity, not the dynamic. There is no analog for the Einstein equations of general relativity and trying to impose the Einstein equations is utterly meaningless.

3. If however, instead of using the energy conditions plus the Einstein equations, you place constraints directly on the Ricci curvature tensor or Einstein curvature tensor then you can still prove versions of the focusing theorems.

4. As in general relativity, the Riemann tensor and its contractions are still useful for characterizing the relative motion of nearby geodesics.

5. The Fresnel drag coefficient can be read off directly from the contravariant components of the metric. Specifically
$$g_{0i} = (n^{-2} - 1)\, \gamma^2\, \vec{v}.$$
For low velocities $\gamma \approx 1$ this implies that the medium drags the light as though the medium had an effective velocity
$$\vec{v}_{\text{eff}} = (n^{-2} - 1)\, \vec{v}.$$
The effective velocity of the medium is just the "shift vector" in the metric. The fact that the Fresnel drag coefficient drops out automatically should not surprise you at all since we are extracting all this from a manifestly Lorentz invariant formalism, and so you must get the same result as from the more usual approach based on the relativistic addition of velocities
$$c_{\text{dragged}} = \frac{v + (c/n)}{1 + \frac{v(c/n)}{c^2}} \approx \frac{c}{n} + (n^{-2} - 1)\, v + O(v^2).$$

6. There are optical analogs of the notions of "trapped surface", "apparent horizon", "event horizon", and "optical black hole" that are in exact parallel to those developed for the acoustic black holes [6,7].

7. If you somehow arrange an "optical event horizon" of this type, then there is near-universal agreement among the quantum field theory community that you should see Hawking radiation from this "optical event horizon", this radiation being in the form of a near-thermal bath of photons with a Hawking temperature proportional to the acceleration of the fluid as it crosses the horizon [6,7] — this is a very exciting possibility, because we would love to be able to do some experimental checks on Hawking radiation.

8. You will be able to probe aspects of *semiclassical quantum gravity* with this technique, but it won't tell you anything about quantum gravity itself. Because an effective metric of this type is not constrained by the Einstein equations it allows you only to probe *kinematic* aspects of how quantum fields react to being placed on a curved background geometry, but does not let you probe any of the deeper *dynamical* questions of just how quantum matter feeds into the Einstein equations to generate real spacetime curvature. Even though it should be kept in mind that these "effective metric" techniques are limited in this sense, they are still a tremendous advance over the current state of affairs.

9. I should mention that I believe the original implementation of Leonhardt and Piwnicki fails to generate genuine black holes, but that this can be straightforwardly corrected [8]. Despite this technical issue, which I believe causes problems for the particular toy model they discussed, it is clear that the basic idea is fine — it is possible to form "optical

black holes" by accelerating a dielectric fluid to superluminal velocities (superluminal in the sense c/n). Any region of superluminal fluid flow will be an ergo-region, and any surface for which the inward component of the fluid flow is superluminal will be a trapped surface.

Finally, let me emphasize the fundamental experimental reason this is now all so interesting: experimental physicists have now managed to get refractive indices up to $n \approx 30,000,000$ which corresponds to $c/n \approx 10$ meters/second [9] — and it is this experimental fact that holds out the hope for doing laboratory experiments in the not too distant future.

References:

[1] U. Leonhardt and P. Piwnicki, Phys. Rev. Lett. **84**, 822-825 (2000).

[2] U. Leonhardt and P. Piwnicki, Phys. Rev. A **60**, 4301–4312 (1999).

[3] U. Leonhardt, *Spacetime physics of quantum dielectrics*, `physics/0001064`.

[4] U. Leonhardt, http://www.st-and.ac.uk/~www_pa/group/quantumoptics/media.html

[5] W. Gordon, Ann. Phys. (Leipzig) **72**, 421 (1923).

[6] W. Unruh, Phys. Rev. Lett. **46**, 1351 (1981); Phys. Rev. D **51**, 2827 (1995).

[7] M. Visser, Class. Quantum Grav. **15**, 1767 (1998); see also `gr-qc/9311028`.

[8] M. Visser, `gr-qc/0002011`

[9] L. V. Lau, *et al*, Nature (London) **397**, 594 (1999).

"Branification:" an alternative to compactification

Steve Giddings, University of California at Santa Barbara giddings@physics.ucsb.edu

Recent developments have breathed new life into the old idea that the observable Universe is embedded in a spacetime with extra large or even infinite dimensions. This raises the exciting prospect that Planckian physics could be observed in high-energy accelerators, provides interesting new techniques to address hierarchy problems in physics, and could possibly lead to novel phenomena in cosmology and black hole physics.

Obstacles to the viability of such a scenario have included explaining why the matter that we see moves only along the 3+1 dimensional hypersurface, and explaining the observed gravitational $1/r^2$ force law characteristic of four dimensions. Old ideas on confinement of gauge fields and fermions to a domain wall have been supplemented with new ones from string theory involving D-branes – these address the first issue. Recall that D-branes are surfaces which open string ends stick to; if observable matter consisted of open strings and the Universe was a D3-brane, that could solve the problem. But gravity is harder to "confine" to a brane-like structure.

One idea that has been actively pursued by Arkani-Hamed, Dimopoulos, and Dvali [3] is that the brane is immersed in space with d extra large but compact dimensions. If the $d+4$ dimensional fundamental Planck mass is M, then the effective four-dimensional Planck mass follows in terms of the compact volume V_d by an elementary argument from the Einstein-Hilbert action:

$$\frac{1}{M^{d+2}}\int dV_{d+4}\mathcal{R} \sim \frac{V_d}{M^{d+2}}\int dV_4\mathcal{R} \ ,$$

giving

$$M_4^2 \sim M^{d+2}V_d \ . \tag{1}$$

An alternative explanation of the weakness of gravity is thus not that the fundamental Planck mass is so big, but rather that the compact volume is big. This raises the exciting prospect that the fundamental Planck scale may be more readily accessible in accelerator experiments, or that the compact dimensions may be detected through experiments with microgravity (see the next article in this issue of MOG).

A new variant of this scheme of even more theoretical interest was proposed by Randall and Sundrum (RS) [4]. In their picture, the brane is instead the Poincare-invariant boundary of a slice of $4+1$ dimensional anti-de Sitter space. RS observed that the negative curvature of anti-de Sitter space plays a very similar role to that of a compact dimension, and effectively binds a graviton mode to the brane. As a result, at low energies matter living on the brane effectively interacts through four-dimensional gravity. The scale at which this ceases to be true, and the underlying infinite fifth dimension is revealed, is set by the anti-de Sitter radius, R. The non-compactness of the extra dimension distinguishes these "branification" scenarios from compactification, and has novel consequences such as the existence of a continuum of "Kaluza-Klein" modes. In analogy to equation (1), we have

$$M_4^2 \sim RM^3 \ ,$$

again raising the possibility that if the anti-de Sitter radius is large enough, the fundamental Planck scale is commensurately lower and Planckian or extra-dimensional physics may be

much more experimentally accessible. Variants of the RS proposal have also been considered, involving either parallel branes in 5 dimensions [5], which may help with the hierarchy problem, or intersecting branes in more dimensions.

Initially there were questions of consistency of this proposal; for example Chamblin, Hawking, and Reall [6] and others observed the existence of black holes arising from matter on the brane with infinitely extended horizons and strong-coupling singularities at the horizon of anti-de Sitter space. However, they also suggested as a possible resolution that these would exhibit a Gregory-Laflamme instability resulting in a solution with horizon confined near the brane. This expectation was confirmed in the case of a 2+1 dimensional brane by Emparan, Horowitz, and Myers [7], and in a linearized analysis by Katz, Randall, and the author [8], who independently found that the horizon of such a black hole is shaped like a pancake. Specifically, its radius along the brane is the familiar $r = 2m$, but the extent transverse to the brane grows only as $R \log m$ with the mass.

These and other checks in the linearized analysis (properties of propagators have been worked out in [8]; other linearized analysis appears in [1] support the consistency of RS branification. Moreover, they raise some interesting possibilities. For example, we, as four-dimensional observers, would see processes through their projection onto the brane. Therefore motion of an object flying around the pancake-shaped black hole through the fifth dimension could be interpreted by four-dimensional observers as motion into one side of the horizon and out the other!

More novelties in cosmology arise because of the extra degrees of freedom associated to motion of the brane or other five-dimensional perturbations of the metric. Initially concerns were raised that the Hubble law came out to be $H \propto \rho$, but more recent work [9,10] has shown that in the presence of extra dynamics that stabilizes the brane's motion we recover the familiar $H \propto \sqrt{\rho}$. More subtle consequences for early Universe physics are being explored, and there have been suggestions that these and related scenarios address the cosmological constant problem [12,13,14]

Finally, the proper setting for branification proposals is presumably string theory, and direct connection has been made to the celebrated AdS/CFT correspondence by Maldacena, Witten, Gubser [2] and [8]. In particular, H. Verlinde [11] has given a closely related proposal within string theory compactified (or perhaps noncompactified?) on a noncompact manifold with an AdS region. Verlinde's scenario deserves more close scrutiny.

Beyond the need to extend understanding of examples of branification in string theory, a number of interesting problems remain both in phenomenology (with a realistic model in hand, what would be the first observable consequence of this picture?); in cosmology, black hole physics and other aspects of the gravitational dynamics in its subtle interplay between four and five dimensions; and finally, with luck, in experiment.

References:

[1] J. Garriga and T. Tanaka, "Gravity in the brane world," `hep-th/9911055`.

[2]S.S. Gubser, "AdS/CFT and gravity," `hep-th/9912001`.

[3] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "The hierarchy problem and new dimensions at a millimeter," `hep-ph/9803315` Phys. Lett. **B429** 263 (1998); "Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity," `hep-ph/9807344`, *Phys. Rev.* **D59**:086004 (1999).

[4]L. Randall and R. Sundrum, "An alternative to compactification," hep-th/9906064, Phys. Rev. Lett. 83 (99) 4690.

[5] J. Lykken and L. Randall, "The shape of gravity," hep-th/9908076.

[6] A. Chamblin, S.W. Hawking, and H.S. Reall, "Brane-world black holes," hep-th/9909205.

[7] R. Emparan, G.T. Horowitz, and R.C. Myers, "Exact description of black holes on branes," hep-th/9911043.

[8] S.B. Giddings, E. Katz, and L. Randall, "Linearized gravity in brane backgrounds," (to appear); for preliminary accounts see S.B. Giddings, talk at ITP Santa Barbara Conference "New dimensions in field theory and string theory," and L. Randall, talk at Caltech/USC conference "String theory at the millennium,"
http://www.itp.ucsb.edu/online/susy_c99/giddings/
http://quark.theory.caltech.edu/people/rahmfeld/Randall/fs1.html.

[9] C. Csaki, M. Graesser, L. Randall, and J. Terning, "Cosmology of brane models with radion stabilization," hep-ph/9911406.

[10] P. Kanti, I.I. Kogan, K.A. Olive, M. Pospelov, "Single brane cosmological solutions with a stable compact extra dimension," hep-ph/9912266.

[11] H. Verlinde, "Holography and compactification," hep-th/9906182.

[12] J. de Boer, E. Verlinde, H. Verlinde, "On the holographic renormalization group", hep-th/9912012; E. Verlinde and H. Verlinde, "RG flow, gravity and the cosmological constant," hep-th/9912018; E. Verlinde, "On RG flow and the cosmological constant," hep-th/9912058.

[13] N. Arkani-Hamed, S. Dimopoulos, N. Kaloper, and R. Sundrum, "A small cosmological constant from a large extra dimension," hep-th/0001197.

[14]S. Kachru, M. Schulz, and E. Silverstein, "Self-tuning flat domain walls in 5-d gravity and string theory," hep-th/0001206.

Current Searches for non-Newtonian Gravity at Sub-mm Distance Scales

Riley Newman, University of California at Irvine
rdnewman@uci.edu

Preface: The possibility that "large" compact dimensions may have a detectable effect on the gravitational force at small distances has stimulated many new experiments (see the previous article in this issue of MOG). A short sketch of activity in this field seemed desirable – of interest to general readers, and of potential use to current practitioners. I have found writing this to be a delicate matter, however. Several groups have understandably been hesitant to make public their activity or plans at this stage – I thank those that consented to go public for this report, and respect the wish of others not to be publicized at this time.

The Report:

John Price (John.Price@Colorado.edu) and his postdoc Josh Long at the University of Colorado are developing an apparatus [1] in which a vibrating reed source mass is driven at the resonant frequency (approximately 1 kHz) of a tungsten plate torsion oscillator separated from it by a gold-plated thin sapphire shield for electrostatic shielding. Capacitive readout of the torsion oscillator amplitude is used. The system operates now at room temperature, later to be at 4K. Mass separations from about 0.1 to 1 mm will be explored, with a target peak sensitivity about 1% of gravity at a range of about 0.3 mm, and equal to gravity at 0.05 mm.

The Padua Group (eg, Giuseppe.Ruoso@lnl.infn.it) measures the influence of a stainless steel source mass on the resonance frequency of a piezo-driven silicon cantilever beam monitored by an optical fiber interferometer. An earlier version of this experiment [2] put a limit on a non-Newtonian force at a level of 8×10^7 of gravity at 0.2 mm. Analysis of results from the current version are underway; Ruoso estimates that the current system is capable of sensitivity at best about 10^6 of gravity; this may be improved in future modifications of the experiment.

John Lipa (John.Lipa@stanford.edu) with S. Wang has built an apparatus at Stanford which, like the current version of the Padua experiment, searches for frequency pulling of a mechanical resonator as a function of field source mass position. A 6.4 mm diameter tungsten disk is attached to a torsional oscillator with resonant frequency 145 Hz and Q 1500, driven capacitively with a phase-locked loop circuit which tracks its resonant frequency. The source mass is a 50 mm diameter tungsten disk, moved at intervals of 20 minutes so that it is alternately 0.1 mm and 1 mm from the test mass. The current sensitivity of the system, operating at room temperature, corresponds to a force magnitude at 0.1 mm less than 10^5 of gravity. A low temperature version of the system is being considered.

Aharon Kapitulnik (ak@loki.stanford.edu) with Tom Kenny is operating a system at Stanford with the following design: A test mass is mounted on a cantilever with very low spring constant ($< 10^{-4} N/m$) within electrostatic shielding, with optical fiber interferometer readout. The source mass is in the form of five squares of mass of alternating specific weight (Al and W), caused to swing periodically laterally about 0.4 mm by a bimorph device. To generate the force signal of interest, the bimorph oscillates at a frequency which is one third of the cantilever's resonance frequency, allowing excellent inertial decoupling. The range of mass separations to be explored is expected to be 0.03 - 0.5 mm. The ultimate sensitivity of the present apparatus design, at 4.2 K, is expected to be better than 5% of gravity at 0.08 mm.

Other designs will be explored in the future.

Eric Adelberger (Eric@gluon.npl.washington.edu) with Blayne Heckel is doing an experiment at the University of Washington using a planar torsion balance that sits above a rotating attractor. The apparatus is not yet completed. Eric's group hopes to be able to probe with good sensitivity force ranges from 0.05 to 2 mm, and expects to have some results in about a year if unexpected problems are not encountered.

Paul Boynton (boynton@u.washington.edu), Michael Moore, and graduate student Micah Ledbetter at the University of Washington are considering an experiment in which the signature of non-Newtonian gravity is a torque on a near-planar torsion pendulum suspended above a near-planar source mass. The signal torque is manifested as a second harmonic distortion of the torsional oscillation of the pendulum. The source and pendulum masses are each to be made with opposing halves at a slightly different elevation, in a configuration which gives a nearly null signal for purely Newtonian gravity. Source and test masses are to be separated by a conducting membrane in the gap between them. The expected sensitivity to an anomalous force is at a level of 0.25 of gravity at 0.25 mm and 10^{-2} of gravity at 1 mm, limited by machining tolerance.

Ho Jung Paik (h_paik@umail.umd.edu) at the University of Maryland has proposed to NSF a mm-scale test for non-Newtonian gravity. The proposed system uses two magnetically levitated 2.1 g Nb test masses 11.6 cm apart, with SQUID readout of their differential motion. Two nearly planar 1.4 kg source masses would be shaped and positioned so that when they are moved in opposite directions their Newtonian effect on the differential motion of the test masses is null. The opposite motion of the source masses cancels inertial reaction forces on the apparatus as a whole, easing vibration rejection requirements for the experiment. The source masses positions will be modulated at about 0.1 Hz. Test masses will be shielded from source masses and environment by superconducting shields. The design sensitivity of the system is 10^{-4} of gravity at 2 mm and 10^{-2} of gravity at 0.1 mm.

Measurements at very short distances. Experiments designed to measure the Casimir force can in principle constrain non-Newtonian gravity, but this is made perilous by uncertainties in accounting for finite conductivity corrections, surface roughness, dirt, etc. Two Casimir force measurements have been made recently:

Steve Lamoreaux (lamore@lanl.gov), used a torsion balance [3] at the University of Washington to measure the force between a 11.3 cm spherical lens and a quartz plate, both plated with copper and then gold, exploring a separation range from 0.6 to 10 microns with results within about 5% of the Casimir prediction. This data has been used by Price and Long [1] and also by Bordag et al. [4] to constrain non-Newtonian gravity – the two analyses appear to disagree somewhat. The figure in [1] suggests a limit of about $10^{5.7}$ of gravity at 100 microns and $10^{7.3}$ of gravity at 10 microns, while a figure in [4] implies tighter respective limits of about $10^{3.4}$ and $10^{6.2}$ of gravity.

Umar Mohideen (umar.mohideen@ucr.edu) with Anushree Roy used an AFM system at UC Riverside to measure [5] the force between a 0.2 mm polystyrene sphere and a sapphire plate, both aluminum coated, over a separation range 100 to 500 nm. The force was measured with an average statistical precision over this range equal to about 1% of the Casimir force at the smallest surface separation, and was found to be consistent with the Casimir force using theoretical corrections calculated to date. Refinements of this work continue.

Michael George (mgeorge@matsci.uah.edu) and his student Lelon Sanderson at the University

of Alabama, Huntsville, are also conducting AFM measurements, and exploring with theorist Al Fennelly the possibility of extracting useful limits on non-Newtonian gravity from these measurements.

M. Bordag et al. (Michael.Bordag@itp.uni-leipzig.de) have attempted [6] to constrain sub-micron scale anomalous interactions, using data from Casimir measurements by others. However, Lamoreaux believes that reliable tests for non-Newtonian gravity can only be made for mass separation greater than 5 or 10 microns, because of uncertainty in corrections at shorter distances.

Ephraim Fischbach (ephraim@physics.purdue.edu) and his colleagues are exploring ideas for circumventing some of the perils in very short distance force measurements, for example by comparing results obtained using different isotopes of the same materials, which should have identical electronic properties but differing gravitational interaction.

Other experiments. There are undoubtably other sub-mm force experiments underway or planned. *Mark Kasevich* (mark.kasevich@yale.edu) at Yale, for example, indicated that he didn't mind being mentioned by name and affiliation, but preferred not to talk in public about his plans which are still somewhat ill defined.

I hope that this sketch of current activity in short distance gravity measurements may be helpful in encouraging communication in an important field.

References:

[1] J.C. Long, H.W. Chan, J.C. Price, Nuclear Physics B **539**, 23 (1999).

[2] C. Carugno, Z. Fontana, R. Onofrio, and C. Rizzo, Phys. Rev. D **55**, 6591, (1997).

[3] S.K. Lamoreaux, Phys. Rev. Lett. **78**, 5 (1997), and Phys. Rev. Lett. **81**, 5475 (1998).

[4] M. Bordag, B. Geyer, G.L. Klimchitskaya, and V.M. Mostepanenko, Phys. Rev. D **58**, 075003 (1998).

[5] A. Roy, C-Y Lin, and U. Mohideen, Phys. Rev. D **60**, 111101 (1999).

[6] M. Bordag, B. Geyer, G.L. Klimchitskaya, and V.M. Mostepanenko, Phys. Rev. D **60**, 055004 (1999).

Quiescent cosmological singularities

Bernd Schmidt, Albert Einstein Institute, Max Planck Society
schmidt@aei-potsdam.mpg.de

In 1964 Penrose and Hawking showed that singularities are a general feature of classes of solutions of Einstein's field equations. Their result said nothing about the structure of those singularities. In the following years much effort was directed to define and analyze "singularities" of spacetimes. However, it turned out that without really using the field equations there were far too many and absurdly complicated possibilities such that it seemed hopeless to attempt a useful classification. In 1970 Belinskii, Khalatnikov and Lifshitz (BKL) gave a heuristic description of a class of singularities based on formal expansions of the metric near a singularity. It remained, however, unclear whether the use of the field equation together with the formal expansions could be justified.

A recent theorem by L. Andersson and A. Rendall [1] shows rigorously that in a particular case, when the matter is described by a scalar field or a stiff perfect fluid ($p = \mu$), the BKL picture is correct. In this particular case there is no oscillatory behavior near the singularity, i.e. a quiescent singularity.

I will describe the theorem and make some remarks about the way it is proved. The theorem uses the notion of "velocity dominated solution" which I will define first. Suppose we have a metric

$$-dt^2 + g_{ab}(t, x^c)dx^a dx^b \ . \tag{1}$$

If we drop all spatial derivatives in the evolution equations, we obtain a system of ordinary differential equations for $g_{ab}(t)$. In the constraints we just drop the Ricci scalar. This system and its solution, ${}^0g_{ab}, {}^0k_{ab} = \partial_t g_{ab}$, is called " velocity dominated". These equations can be integrated completely and the solutions and their singularities can be described explicitly. One has in general ${}^0k^a_a = (C - t)^{-1}$. We can chose $C = 0$ to have the singularity occur at $t = 0$. Furthermore all mixed components ${}^0k^b_a$ are proportional to t^{-1}. At a fixed spatial point we can simultaneously diagonalize ${}^0k_{ab}$ and ${}^0g_{ab}$ by a suitable choice of frame. The diagonal components of the metric in this frame are then proportional to powers of t. The equation for the matter field can also be integrated with the result ${}^0\phi(t, x^a) = A(x^a) \log t + B(x^a)$.

Now we can formulate the main theorem:

Theorem: *Let S be a three-dimensional analytic manifold and $({}^0g_{ab}(t), {}^0k_{ab}(t), {}^0\phi(t))$ a C^ω solution of the velocity dominated Einstein–scalar field equations on $S \times (0, \infty)$ such that $t\,{}^0k^a_a = -1$ and each eigenvalue λ of $-t\,{}^0k^b_a$ is positive. Then there exists an open neighborhood U of $S \times \{0\}$ in $S \times [0, \infty)$ and a unique C^ω solution g_{ab}, k_{ab}, ϕ of the Einstein–scalar field equations on $U \cap (S \times (0, \infty))$, such that for each compact subset $K \subset S$ there are real positive numbers β and $\alpha^a{}_b$ with $\beta < \alpha^a{}_b$ for which the following estimates hold uniformly on K:*

1. ${}^0g^{ac}g_{cb} = \delta^a{}_b + o(t^{\alpha^a{}_b})$
2. $k^a{}_b = {}^0k^a{}_b + o(t^{-1+\alpha^a{}_b})$
3. $\phi = {}^0\phi + o(t^\beta)$
4. $\partial_t\phi = \partial_t\,{}^0\phi + o(t^{-1+\beta})$

together with similar estimates for spatial derivatives of g_{ab} and ϕ.

Each velocity dominated solution is approached by a unique solution of the full equations. Hence, the singularity structure of the full solution is the same as that of the velocity dominated solution. There are indications that conversely, each solution approaches a velocity dominated solution. The behavior of the curvature tensor near the singularity is

$$R_{ab}R^{ab} = K(x^a)\ t^{-4} + \dots$$

The solution is really singular at $t = 0$ and the BKL picture is justified in the cases considered. The proof of the theorem relies on a result by Kichenassamy and Rendall [2]. It concerns a system of the form $(u = (u^1 \dots u^N),\ x = (x^1, \dots x^n))$

$$t\ \frac{\partial u}{\partial t} + A(x)\ u = f(t, x, u, u_x)$$

Under appropriate conditions, this singular equation has a unique solution near $t = 0$ which is continuous in t and tends to zero as $t \to 0$. To use this theorem one rewrites the field equations as equations for the "difference between the solution and the velocity dominated solution". Hence regular equations for a singular solution are replaced by a singular equation for a regular solution.

New mathematical tools allow fresh investigations of the properties of singularities of solutions of Einstein's field equations. Hopefully, this technique can also be used to treat the more complicated cases of an oscillatory behavior of the metric near the singularity.

References:

[1] Andersson, L. and Rendall, A. D. Quiescent cosmological singularities. `gr-qc/0001047`.

[2] Kichenassamy, S. and Rendall, A. D. (1998) Analytic description of singularities in Gowdy spacetimes. Class. Quantum Grav. 15, 1339–1355

The debut of LIGO II

David Shoemaker, MIT
dhs@ligo.mit.edu

From its beginning, LIGO was foreseen as capable of supporting a series of ever-improving detectors over a lifetime of many years. The LIGO I detector, now being installed, is the exciting first step of this process. LIGO I uses techniques developed and tested in sensitive prototypes, begun nearly 30 years ago, and will have a sensitivity several orders of magnitude greater than any of the gravitational wave detectors which helped lead to its design. Coincident operation of the three interferometers at the two LIGO observatories will start in 2002, in coordination with the VIRGO [1] detector and the GEO-600 [2] detector.

Simultaneous with this development of LIGO I, plans for the more ambitious LIGO II are gaining momentum. The LIGO Scientific Collaboration [3] has been refining the vision of what technical advances would constitute a significant step forward and forming the research plan which can realize these advances; and the LIGO Laboratory has studied the practicalities of actually fabricating, installing, commissioning, and observing with a new detector. An introduction to this vision of LIGO II is presented in this article. Readers interested in delving further can investigate the LSC White Paper [4] and the Laboratory Conceptual Plan [5].

A look at the anticipated sensitivity of LIGO I (seen at right in Figure 1, top curve) shows three regions; the near-vertical line at low frequencies, a midrange from 40 to 120 Hz, and a high frequency region above 120 Hz. Let's look at how the LIGO II design improves the performance in each of these regions, starting from the high frequency end. The design we talk about here is a starting point, rather than a definition of LIGO II; and we have already been alerted to one missing component in our model, and anticipate greater thermal noise than indicated in these curves. With that caveat, here are the broad outlines of what we hope to achieve with LIGO II.

Shot Noise Dominated Region

LIGO I uses 10 W of laser power in a power-recycled Michelson interferometer with Fabry-Perot arm cavity transducers to sense the motion of the test masses. The limit to our ability to sense comes from the "shot noise limit"–the (Poisson) statistical fluctuation in the number of photons arriving at our photodetector makes us uncertain about the exact position of the test masses. Increasing the laser power decreases the fractional uncertainty, as the square root of the laser power, and so an obvious improvement in a second-generation interferometer is to increase the laser power. The Reference Design for LIGO II, shown in the LSC White Paper [4], carries an increase from 10 to 180 W of input laser power, and also takes advantage of the best optical polishing and coating to date to allow a lower-loss optical system (and thus a higher "recycling gain"). These changes lead to a better sensing of the test mass motion, and as seen in Figure 1 a much-improved high-frequency sensitivity. They also require considerable research and development in optical components: low-noise laser amplifiers, phase modulators, Faraday isolators, and the means to compensate for thermal lensing of the interferometer components. However, this is not the only change. There are several curves for LIGO II shown in Figure 1. This is due to the addition of a Signal Recycling Mirror, as seen at left in Figure 2. The power recycling mirror allows unused input power to be "recycled" into the interferometer, a technique used in both LIGO I and II. For LIGO II, the additional

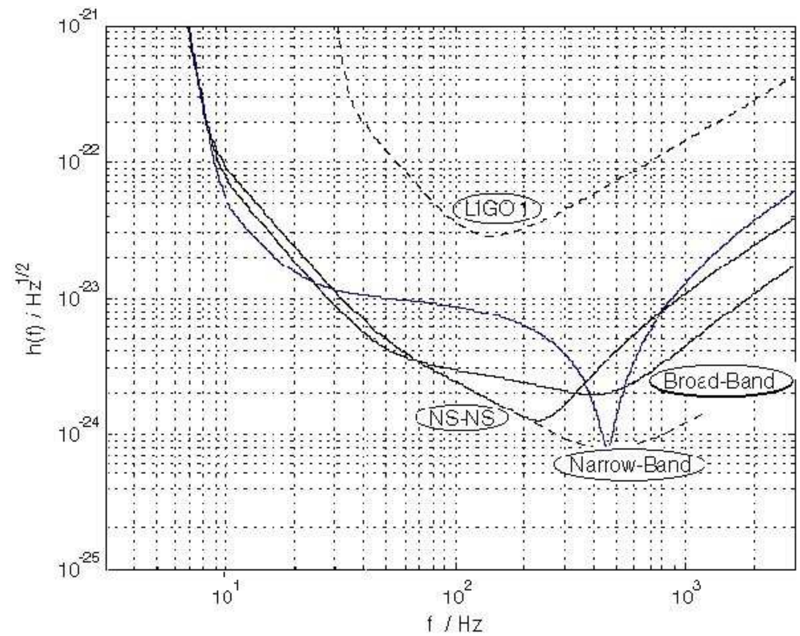

Figure 1: LIGO I and II sensitivities

signal recycling mirror can be used either to “recycle” (signal recycling), or intentionally “extract” (resonant sideband extraction) the actual gravitational-wave induced signal to selectively increase the sensitivity of the instrument for a specific signal search. This leads to the collection of curves shown in Figure 1: one can make a frequency response curve which is optimized for, say, a Neutron Star Binary inspiral event (NS-NS), a broad-band source such as a Supernova (Broad-Band), or target a specific frequency (Narrow-Band). These changes are made through sub-wavelength position changes in the signal recycling mirror position and/or changes in the effective transmission.

A series of experiments and detailed models have been underway for some time to both verify the usability of these configurations and to find a suitable practical form. A significant effort in the Ligo Science Collaboration Research and Development will be in the establishment of high-sensitivity prototypes to give confidence in the design and to test engineering solutions.

We need to delve a little deeper to see a complement to the shot noise, the radiation pressure noise. Figure 3 at right shows the aforementioned shot noise contribution to the sensitivity; curve 7 shows the effect of momentum transfer from the photons to the test masses. The mass motion due to this noise source dominates at low frequencies, until shot noise takes over at about 100 Hz. This “buffeting” of the masses *grows* with the laser power (again as the square root of the power), and so it becomes clear that an optimum laser power exists–a power such that the sensing noise at high frequencies is reduced to an acceptable level, but one where the low-frequency buffeting of the test masses by radiation pressure is not so great as to impact the low-frequency performance. We call the LIGO II design “a quantum limited interferometer” due to the fact that at all frequencies the LIGO II sensitivity is limited by the quantum nature of light. Since the buffeting is a force, it makes sense that this noise source falls as $1/f^2$ and that the motion associated with it becomes smaller if the mass is greater.

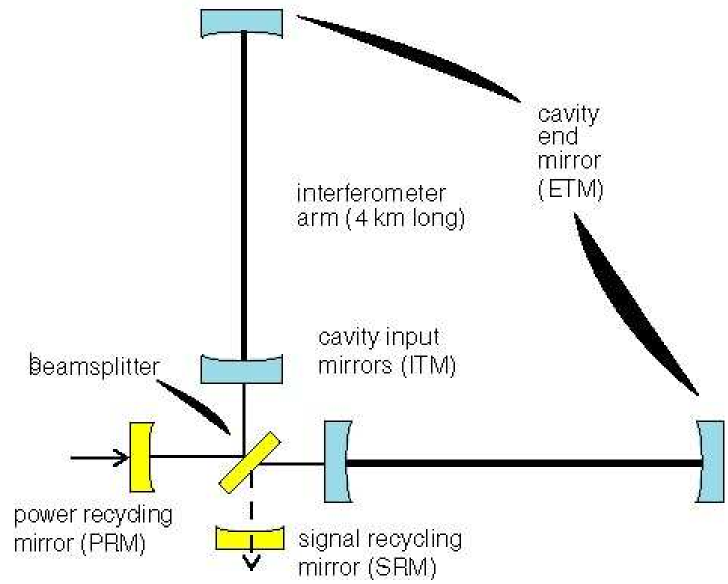

Figure 2: Signal recycling setup

This leads us to the second significant change from LIGO I: the test masses are to be 30 kg, rather than LIGO I's 10 kg, to hold down the radiation pressure noise (and allow a higher laser power).

Thermal Noise

Over a broad range of frequencies, the sensitivity of LIGO I will be limited by the Brownian motion, and the related noise due to thermoelastic dissipation, of the test masses. The test masses are in thermal equilibrium with the surrounding heat bath (at a carefully regulated 20 degrees Celsius), and thermodynamics tells us that each mechanical mode of the test masses (and their wire loop pendulum suspensions, in the case of LIGO I) has kT of energy (where k is Boltzmann's constant). This energy is expressed as a random motion of the test mass, where the distribution of the motion as a function of frequency is determined by details of the losses which limit the mechanical Q of the system (test mass or suspension). To reduce this noise, one wants to "gather" the noise into the peak near the mechanical resonances (by choosing materials and processes which maximize the mechanical Q) and place the resonances either below the frequencies of interest (the pendulum suspension modes, around 1 Hz) or well above the frequencies of interest (the test mass internal modes, 10 kHz and higher).

This introduces two very important changes from LIGO I. First, we are studying the use of sapphire instead of fused quartz for the test mass material. Sapphire has very low mechanical losses, and also a high speed of sound and a high density. These are all advantageous for the thermal noise, and the increased mass is needed for the radiation pressure noise. However, to obtain sapphire in the size required for a LIGO test mass (order of 28 cm diameter, 12 cm thickness) and of an optical quality sufficient for the interferometric sensing, requires a development effort, but will be rewarded with a much reduced thermal noise. (Curve 4, Fig

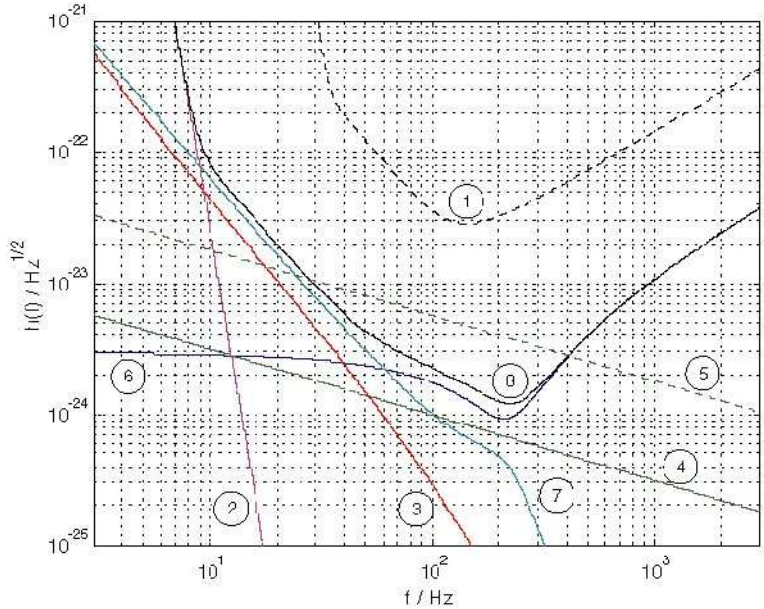

Figure 3: The various components of the noise

3 shows an estimate for the thermal noise not including the thermoelastic term, which will increase the level by factors of 3 to 10 depending upon the frequency). For reference, the thermal noise for 30 kg fused silica masses is also shown (curve 5); realizing this alternative test mass material would require physically large test masses and presents different fabrication challenges.

The second change is to use fused quartz instead of steel wire for the suspension, and to use a ribbon rather than a simple cylindrical fiber. Fused quartz is a much lower loss material than wire, and making a ribbon allows the suspension to be very "soft" along the optical path (to store little energy in stiffness of the ribbon itself, and instead to use gravity as a restoring force for the pendulum motion) and thus to further reduce the thermal noise from the fiber (curve 3, Fig 3). The suspension and its design, shown in Figure 4 at right, uses multiple masses and multiple fibers, and is a contribution from our close collaborators of the German-Scots GEO group; a similar design will be first tried in the GEO-600 interferometer.

Seismic Noise

The requirement for the attenuation of seismic noise is to make it a negligible contributor to the overall interferometer performance. Thus it must be small at all frequencies where other, more difficult and subtle noise sources (like quantum or thermal noise) are at a level allowing the observation of probable gravitational wave sources. For LIGO I, this led to a "cutoff" or "brick wall" frequency of 40 Hz–at all lower frequencies, the thermal noise would have been so great that no reasonable model for gravitational wave sources would predict detectable signals. For LIGO II, due to the much reduced thermal noise and managed radiation pressure noise, a cutoff frequency of 10 Hz is a good choice (curve 2, Fig 3). This puts the seismic noise

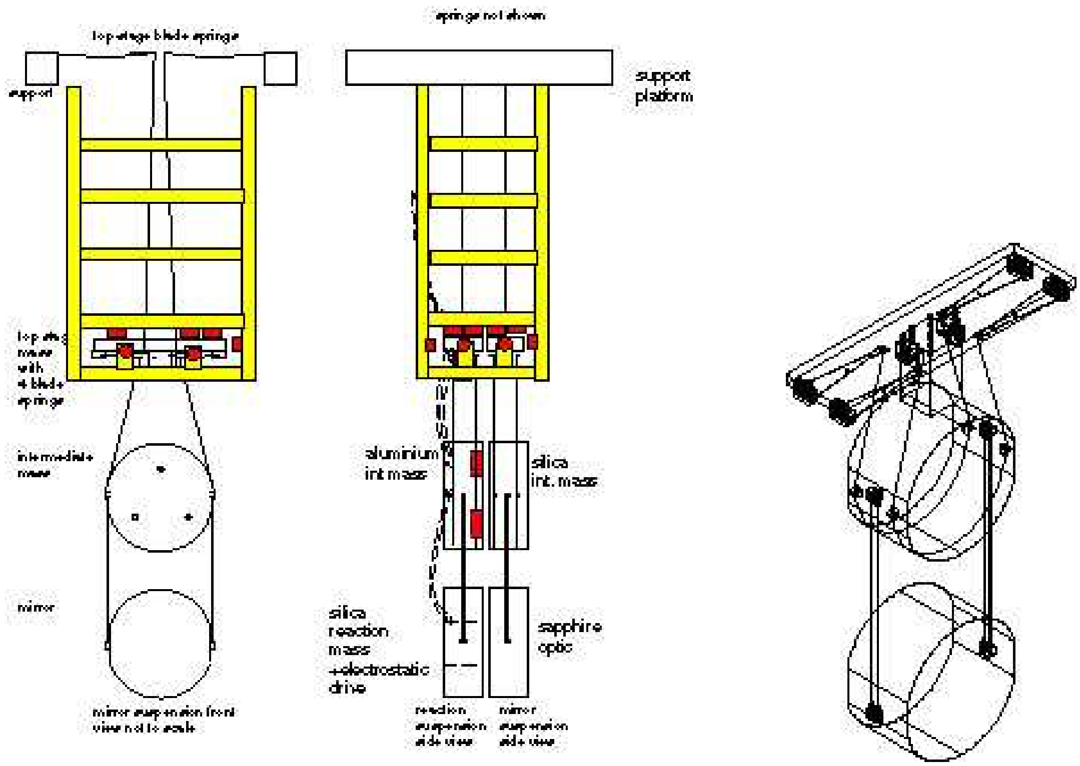

Figure 4: The suspension systems

contribution at 10 Hz close to the background due to the Newtonian background–dynamic changes in the net direction of the gravitational attraction of the test mass to the earth due to compression and rarefaction of the nearby earth as normal seismic motion takes place.

There are two approaches to the seismic attenuation under study. One uses passive isolation, in a design derived from that used by the VIRGO project; the other uses servo control techniques to slave the quiet suspension platform to quiet seismometers. The final design must deliver the required reduction in both the seismic noise near 10 Hz as well as fulfilling the very important role of reducing motion for frequencies 1 Hz and lower as part of the overall control approach.

To verify the mechanical design of the experiment, a prototype allowing tests of the suspension and isolation components of LIGO II is in preparation. The objective, as for the configuration prototypes mentioned above, is to allow a demonstration of the performance levels of LIGO II without disturbing observation underway with LIGO I.

Physics Reach

The resulting interferometer (or detector, as interferometers at both the LIGO Livingston, Louisiana and Hanford, Washington observatories will be improved) will offer an enormous increase in the sensitivity to many gravitational wave sources. In one coarse measure, the strain sensitivity to broad-band sources in the region of 100 Hz will increase by a factor of many factors of 10. Because the included volume of space goes as the cube of the distance, this means we include many, many times more candidate sources with LIGO II as compared to LIGO I. Also, the "tunability" of the response means that, as we learn more about specific sources, we can increase our sensitivity even more dramatically for those sources. Sources which might be observable by LIGO I once per year would be observed many times every day by LIGO

II, and the signal-to-noise ratio may allow detailed studies of the waveform for comparison with numerical models, leading to better understanding of both astrophysics and of physics in highly relativistic conditions. The LIGO II detector will be run in cooperation with the other gravitational-wave detectors to form a powerful network, permitting the extraction of position, polarization, and other source parameters from the combined data.

The plan is an ambitious one. We would like to start the replacement of the LIGO I interferometers with the LIGO II design in 2005 and be observing before 2007. This schedule will need exquisite preparation to minimize the "down time" for observation to a minimum and to assure that the LIGO II interferometer will perform as designed as quickly as possible after installation. Close coordination of the Research and Development leading to a final design is a pre-requisite, and "all-hands" must be available for the well-rehearsed installation. The results will be very satisfying of course as a technical achievement–but more importantly, they will be extraordinarily rich in astrophysical insights.

References:

[1] http://www.pg.infn.it/virgo/

[2] http://www.geo600.uni-hannover.de

[3] http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html

[4] http://www.ligo.caltech.edu/docs/T/T990080-00.pdf

[5] http://www.ligo.caltech.edu/docs/M/M990288-A1.pdf

Is the universe still accelerating?

Sean Carroll, University of Chicago
carroll@theory.uchicago.edu http://pancake.uchicago.edu/~carroll/

To most cosmologists, it came as something of a surprise when, in 1998, two groups (the Supernova Cosmology Project [1] and the High-Z Supernova Team [2,3] presented evidence that the expansion of the universe is accelerating rather than slowing down. Applied to a Robertson-Walker metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + R^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega^2\right] , \tag{1}$$

Einstein's equations imply the Friedmann equation,

$$\dot{R}^2 = \frac{8\pi G}{3}R^2\rho - k , \tag{2}$$

where R is the scale factor, ρ the energy density, and k the spatial curvature parameter. The energy density in a species of non-relativistic massive particles ("matter") is given by the species' rest mass times its number density, and correspondingly diminishes as $\rho_{\mathrm{M}} \propto R^{-3}$ as the number density becomes increasingly rarified. In a matter-dominated universe, then, the right-hand side of (2) is decreasing as the universe expands, resulting in deceleration. To provide acceleration ($\ddot{R} > 0$), the energy density must decay more slowly than R^{-2}; the simplest candidate for such a source is the cosmological constant Λ, equivalent to a "vacuum" energy density

$$\rho_\Lambda = \frac{\Lambda}{8\pi G} , \tag{3}$$

which remains constant as the universe expands. The supernova teams have measured the distances to cosmological supernovae by using the fact that the intrinsic luminosity of Type Ia supernovae, while not always the same, is closely correlated with their decline rate from maximum brightness, which can be independently measured. Their apparent magnitude then provides an indication of their distance, and their redshift z (related to the value of the scale factor R at the time of explosion by $z = R_0/R - 1$) can be straightforwardly determined from spectroscopic data. The results to date favor a positive value of ρ_Λ. Along with constraints on the matter density as derived from dynamical measurements of galaxies and clusters, and additional constraints from the anisotropies of the cosmic microwave background, a consistent picture emerges with $\rho_\Lambda/\rho_{\mathrm{M}} \sim 3$, with the total energy density $\rho_{\mathrm{M}} + \rho_\Lambda$ approximately equal to the critical density necessary to solve (2) with $k = 0$.

Despite its excellent fit to the data, such a universe seems quite unnatural. For one thing, the implied vacuum energy $\rho_\Lambda \sim 10^{-10}$ erg/cm^3 is less by many orders of magnitude than any sensible estimate based on particle physics. For another, ρ_{M} and ρ_Λ evolve at different rates, with $\rho_{\mathrm{M}}/\rho_\Lambda \propto R^{-3}$, and it would seem quite unlikely that they would differ today by a factor of order unity. Since any effect which would diminish the brightness of distant supernovae without noticeably affecting their spectra could mimic the effects of an accelerating universe, it is sensible to ask whether these apparently dramatic results can be explained in terms of conventional astrophysics without invoking new cosmological phenomena. The most plausible candidates for such effects are evolution of the supernova population from high to

low redshifts, and obscuring dust between us and the high-redshift objects. Both possibilities are being carefully investigated.

Type Ia supernovae are thought to result from thermonuclear explosions of white dwarfs which have reached the Chandrasekhar limit. Therefore, they can occur in a wide variety of environments, and a simple argument against evolution is that the high-redshift environments, while chronologically younger, should be a subset of all possible low-redshift environments, which include regions that are "young" in terms of chemical and stellar evolution. Nevertheless, even a small amount of evolution could ruin our ability to reliably constrain cosmological parameters [4]. In their original papers [1,2,3], the supernova teams found impressive consistency in the spectral and photometric properties of Type Ia supernovae over a variety of redshifts and environments (*e.g.*, in elliptical vs. spiral galaxies). More recently, however, Riess *et al.* [5] have presented tentative evidence for a systematic difference in the properties of high- and low-redshift supernovae, claiming that the risetimes (from initial explosion to maximum brightness) were higher in the high-redshift events. It is not immediately clear that such a difference is relevant to the distance determinations; first, because the risetime is not used in determining the absolute luminosity at peak brightness, and second, because a process which only affects the very early stages of the light curve is most plausibly traced to differences in the outer layers of the progenitor, which may have a negligible affect on the total energy output. Nevertheless, any indication of evolution brings into question the fundamental assumptions behind the entire program. However, Aldering *et al.* [6] have argued that the discrepancy in risetimes goes away once one properly takes into account correlations in the uncertainties of the light curve fit parameters. In that case, all of the data presently available are consistent with no evolution of any sort between high and low redshifts. It is clearly important to improve both our empirical and theoretical understanding of the high-redshift supernovae, but to date there is no compelling reason to doubt the distance determinations (and cosmological conclusions) of the original studies.

Other than evolution, obscuration by dust is the leading concern about the reliability of the supernova results. Ordinary astrophysical dust does not obscure equally at all wavelengths, but scatters blue light preferentially, leading to the well-known phenomenon of "reddening". Spectral measurements by the two supernova teams reveal a negligible amount of reddening, implying that any hypothetical dust must be a novel "grey" variety. This possibility has been investigated by a number of authors [7] These studies have found that even grey dust is highly constrained by observations: first, it is likely to be intergalactic rather than within galaxies, or it would lead to additional dispersion in the magnitudes of the supernovae; and second, intergalactic dust would absorb ultraviolet/optical radiation and re-emit it at far infrared wavelengths, leading to stringent constraints from observations of the cosmological far-infrared background. Moreover, even relatively grey dust would inevitably lead to some reddening, and recent near-infrared observations of a high-reshift supernova [8] have failed to find any evidence for such an effect. Thus, while the possibility of obscuration has not been entirely eliminated, it requires a novel kind of dust which is already highly constrained (and may be convincingly ruled out by further observations).

Meanwhile, measurements of the anisotropy spectrum of the cosmic microwave background continue to improve. Two groups [9] have reported measurements on the angular scale of the first "Doppler peak", whose location is tied to the total energy density of the universe. Both experiments provide independent evidence that the energy density is approximately equal to the critical density of a spatially flat universe; along with increasing confidence that

ordinary matter constitutes approximately 30% if the critical density, this provides additional support for the existence of a positive cosmological constant. Data to come in the near future, from satellite, ground-based, and balloon-borne experiments, will test this scenario to much greater precision. Measurements of additional supernovae at even higher redshifts have the potential of separating out the effects of evolution and extinction from those of cosmology; along with continued ground-based and Space Telescope observations, a dedicated satellite has been proposed [10] which could observe 2000 high-redshift supernovae per year. Our best current understanding, therefore, continues to favor an accelerating universe, and in a short while the case could be nailed down to a near certainty; in that case the task of theorists to explain a small but nonzero vacuum energy will become especially urgent.

References:

[1] S. Perlmutter *et al.* [Supernova Cosmology Project Collaboration], Astrophys. Journ. **517**, 565 (1999); `astro-ph/9812133`.

[2] B. P. Schmidt *et al.* [Hi-Z Supernova Team Collaboration], Astrophys. Journ. **507**, 46 (1998); `astro-ph/9805200`.

[3] A.G. Riess *et al.* [Hi-Z Supernova Team Collaboration], Astron. Journ. **116**, 1009 (1998); `astro-ph/9805201`.

[4] P. S. Drell, T. J. Loredo and I. Wasserman, `astro-ph/9905027`.

[5] A. G. Riess, A. V. Filippenko, W. Li and B. P. Schmidt, Astron. Journ. **118**, 2668 (1999); `astro-ph/9907038`.

[6] G. Aldering, R. Knop and P. Nugent, `astro-ph/0001049`.

[7] A. Aguirre, Astrophys. Journ. **512**, L19 (1999); `astro-ph/9811316`; Astrophys. Journ. **525**, 583 (1999); `astro-ph/9904319`; A. Aguirre and Z. Haiman, `astro-ph/9907039`; J.T. Simonsen and S. Hannestad, Astron. Astrophys. **351**, 1 (1999); `astro-ph/9909225`; T. Totani and C. Kobayashi, Astrophys. Journ. **526**, L65 (1999); `astro-ph/9910038`.

[8] A.G. Riess *et al.*, `astro-ph/0001384`.

[9] A. D. Miller *et al.*, Astrophys. Journ. **524**, L1 (1999); `astro-ph/9906421`; A. Melchiorri *et al.*, `astro-ph/9911445`.

[10] See the web page at http://snap.lbl.gov/

Journées Relativistes Weimar 1999

Volker Perlick, TU Berlin and Albert Einstein Institute, Max Planck Society
vper0433@itp0.physik.tu-berlin.de

The "Journées Relativistes" started as a regular meeting of French relativists several decades ago. Over the years, they have grown into a series of international conferences held in various Western-European cities. The most recent meeting in this series took place in Weimar, Germany, from September 12 to September 17, 1999. The main organizers were G. Neugebauer (Chairman) and R. Collier (Secretary) from the relativity group in Jena. The conference was sponsored by the *Max Planck Society*, by the *Deutsche Forschungsgemeinschaft*, by the *Ministry for Science, Research, and Culture* of the state of Thuringia, Germany, and by the *Friedrich Schiller University* at Jena.

Weimar is a city of approximately 60,000 inhabitants, situated some 20 kilometers west of Jena in the state of Thuringia. The meeting took place in a hotel at the outskirts of Weimar so that most participants stayed together not only during the day but also during the evening. As a consequence, there was ample time for vivid discussions in a pleasant atmosphere. On Thursday afternoon there was no scientific program; instead, everyone had the opportunity to visit the city, either with an organized tour or on his or her own. Weimar is best known for its cultural tradition, given the fact that, among others, J. S. Bach, J. W. Goethe, F. Schiller, and F. Liszt spent at least some years in this city and left their traces in various places. For this reason, Weimar is visited by a large number of tourists every year. In the year of the conference this number was even higher than usual because Weimar was nominated "European City of Culture 1999" by the European Union. Incidentally, the same fact had a somewhat unwanted impact on the beer prices.

This meeting in Weimar clearly demonstrated the international character of the "Journées Relativistes". It was attended by participants not only from Western Europe but also from Eastern-European countries, from various parts of the former Soviet Union, and from both Americas. The total number of participants came up to almost 100 which was even slightly beyond the seating capacity of the lecture room.

Following the tradition of earlier meetings in this series, the conference covered all aspects of general relativity. The scientific program was divided into morning sessions with invited plenary lectures of 60 minutes or of 30 minutes, two parallel afternoon sessions with contributed talks of 30 minutes, and poster sessions. In the following I give a brief overview on the morning sessions.

The conference started with a welcome address by G. Neugebauer (Jena) and a speech by R. Kerner (Paris) honoring the late André Lichnerowicz. The first scientific talk was by Y. Choquet-Bruhat (Paris) on the so called "null condition" and its relevance in view of the Christodoulou-Klainerman result on the global existence of solutions to Einstein's vacuum field equation which are close to Minkowski space. Classes of solutions to Einstein's field equation were investigated also in the following talks. H. Friedrich (Golm) considered asymptotically flat solutions and showed how to calculate some asymptotic quantities near spacelike infinity. J. Bičák (Prague) reviewed some recent developments in the investigation of radiative spacetimes. D. Kramer (Jena), stepping in as a plenary speaker for Lee Lindblom who could not attend the meeting, presented an axially-symmetric gravitational wave solution. Z. Perjés (Budapest) talked about general properties of rotating perfect fluid solutions and on strate-

gies of finding such solutions that may serve as models of rotating stars. For the idealized case of a rigidly rotating disk of dust, this problem was solved by Neugebauer and Meinel a few years ago. G. Neugebauer (Jena) in his talk elucidated that this was possible by viewing the whole problem as a boundary value problem for the exterior vacuum region and rewriting this as a Riemann-Hilbert problem. R. Meinel (Jena) in his talk discussed the properties of this disk-of-dust solution in a common setting with the Kerr solution. (There was also a video presentation in one of the afternoon sessions by M. Ansorg (Jena) and D. Weiskopf (Tübingen) visualizing the optical appearance of the Neugebauer-Meinel disk to an outside observer.)

Various aspects of black holes were at the center of a second group of talks. Th.Damour (Paris) spoke on a correspondence between self-gravitating string states and Schwarzschild black holes. D. Brill (Maryland) presented solutions to the $(2+1)$-dimensional source-free Einstein equation that are constructed by gluing together several black-hole configurations. W. Israel (Victoria) discussed some aspects of the thermodynamics of spinning black holes. G. Schäfer (Jena) reported on his results with P. Jaranowski, presenting the dynamics of binary black-hole systems to within 3rd post-Newtonian approximation. B. Brügmann (Golm) gave a status report on results of the so-called Grand Challenge Alliance, aiming at numerically investigating dynamical processes such as binary black-hole mergers.

Quantum field theory on a classical spacetime background was the topic of the talk by V. Belinski (Moscow) who critically discussed various derivations of the Unruh effect. In addition, there were two talks aiming at quantizing the gravitational field itself. S. Deser (Brandeis) talked about ultraviolet divergences in quantum (super-)gravity, indicating the necessity of stringlike, nonlocal, extensions. A. Ashtekar (Penn State) considered spacetimes with “isolated horizons”, a notion which generalizes the event horizons known from the theory of static black holes, and the non-perturbative quantization of such objects.

Another group of talks can be summarized under the heading “cosmology”. This includes a review on the microwave background radiation and its anisotropies by N. Deruelle (Paris) and a talk on how to find limits for the cosmological parameters with the help of gravitational lens statistics by N. Straumann (Zürich). The foundations of gravitational lens theory from a spacetime perspective, concentrating on the geometry of light cones, were discussed by J. Ehlers (Golm). There were two more talks with a relation to cosmology. B. Carter (Paris) discussed various aspects of cosmic strings, and M. Demiański (Warsaw) reviewed the history of the gravitational constant.

The program was rounded out by one plenary talk on experimental aspects of gravity. H.-P. Nollert (Tübingen) gave an overview on the prospects of gravitational wave astronomy.

Further information can be found on the conference homepage

`http://www.tpi.uni-jena.de/tpi/journees-relativistes.html`

Written versions of all presentations (invited talks, contributed talks, and posters) that survive a refereeing process will be published in a double issue of *Annalen der Physik* (*Leipzig*).

The 9th Midwest Relativity Meeting

Thomas Baumgarte, University of Illinois at Urbana-Champaign
thomas@astro.physics.uiuc.edu

The 9th Midwest Relativity Meeting was hosted by Stu Shapiro, Thomas Baumgarte and the Illinois Relativity Group at the Department of Physics of the University of Illinois at Urbana-Champaign on November 12 & 13, 1999. With about 80 participants and over 50 presentations it was the largest Midwest Relativity Meeting so far. A list of participants, program, and transparencies of all the talks can be found at the conference's website `http://www.pws.uiuc.edu/groups/relativity/MRM9/`.

In the tradition of the regional meetings in the US there were no parallel sessions, and all talks were limited to 10 minutes, plus 5 minutes for questions. The talks were grouped into nine sessions, covering gravitational waves, numerical relativity (two sessions), energy and entropy, relativistic astrophysics, perturbative methods, cosmology, mathematical relativity and quantum gravity, and mathematical and theoretical issues. In the following I will briefly mention some of the most interesting contributions, and I apologize to all those speakers who I have left out.

John Friedman started off the meeting with a summary of recent work on unstable r-modes in rotating neutron stars. Fred Lamb later picked up the story and reported on possible limits to r-mode instabilities due to magnetic fields. After a brief update on the current status of the LISA project, Peter Bender discussed the prospect of detecting gravitational waves from massive black holes and their coalescence. Bill Hiscock discussed MACHOs in the Galactic halo as sources of low frequency gravitational waves, which may also be detectable by LISA.

A number of interesting new results were presented in the two sessions on numerical relativity, demonstrating that numerical relativity is now able to address longstanding, three-dimensional problems in gravitational physics and astrophysics. Stu Shapiro presented results on the stability and collapse of relativistic, rotating neutron stars. Masaru Shibata discussed fully relativistic simulations of binary neutron star mergers. His results suggest that the merger may lead to a very massive neutron star as opposed to a prompt collapse to a black hole. Thomas Baumgarte showed how such "hyper-massive" neutron star can be stabilized against collapse by virtue of differential rotation. Walter Landry demonstrated that a particular implementation of a higher order diffusion term can stabilize the otherwise unstable numerical evolution of the ADM equations. Simonetta Fritelli showed how recent, conformally decomposed versions of the ADM equations, which have shown much better numerical behavior than the original ADM equations, can be cast into a first-order well-posed form. Wai-Mo Suen, Mark Miller and other members of the Washington University group presented updates on the status of the NASA Neutron Star Grand Challenge Project, including simulations of coalescing neutron stars. Roberto Gomez discussed horizon data for black hole collisions, and Mijan Huq presented simulations of grazing collisions of black holes.

Bob Wald presented a generalization of the "Bousso bound" (or "holographic bound") on the entropy flux through a null hypersurface. Robert Mann showed how the entropy, energy and angular momentum of Misner strings emerge from boundary terms of the gravitational action in the AdS/CFT correspondence. Matt Visser demonstrated how certain quantum effects and even some classical systems can lead to violations of all the energy conditions of general relativity, and Carlos Barcelo discussed some of the consequences.

Shmulik Balberg discussed the effect of accretion onto black holes in core-collapse supernovae on the supernova light curve. In particular, he pointed out that for SN1997D in NGC1536 these effects may well be observable in the next year. Draza Markovic presented results on gravitomagnetic warping modes of inner accretion disks, which may explain the quasi-periodic X-ray brightness oscillations observed in X-ray binaries.

Eric Poisson and Bill Laarakkers discussed how the presence of a cosmological horizon in Schwarzschild-deSitter spacetimes affects the radiative falloff of a massless scalar field.

Leonard Parker explained how non-perturbative terms in the vacuum energy-momentum tensor of a quantized field can cause an acceleration of the recent expansion of the universe, and Alpan Raval showed how this model fits current cosmological observations, including data from high-redshift Type Ia supernovae.

I think that it was a very interesting and lively meeting, enjoyable even for the organizers. They would especially like to thank the Department of Physics at the University of Illinois once again for its generous support of this meeting. The 10th Midwest Relativity Meeting will be hosted by Beverly Berger and David Garfinkle at Oakland University, tentatively scheduled for Oct. 27 & 28 2000.